5

Chernozems, Carbon, Climate

"...the soil is the nursery, a store room of the food supply, a bridal-hall, and the cemetery of the biosphere."
Constantin Nikiforoff (1942)

Constantin Nikiforoff mostly studied soil physico-chemical attributes in relation to soil formation and the pattern of soil cover. But he also wrote about soil organic matter and Chernozems. He had studied the iconic soils in Russia, in Minnesota and Washington State and wrote a review on how Chernozems formed, and the significance of humification, accumulation of soil organic matter, and calcium carbonate. The focus was on soil organic matter and how it was affected by short-term soil-related processes, and long-term geochemical cycles. He also reviewed soil-climate relationships, motivated by his interest in climatic effects on soil formation, not so much by the effects of soils on climate.

5.1 Chernozems

Eugene Hilgard used the term Chernozem in his 1906 book *Soils, their Formation, Properties, Composition, and Relation to Climate, and Plant Growth* [1]. He described the organic matter content in soils of different climatic regions; in drylands, soil organic matter was destroyed by oxidation, for which he used the term eremacausis, so, soils in arid regions were low in humus. His review of the Chernozems of Russia was based on the publications of geobotanist Pavel Kostychev (1845–1895) who considered soil

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texture more important than climate in the formation of Chernozems [2, 3]. Pavel Kostychev had proposed that mainly plant roots were responsible for the accumulation of organic matter in soils. Eugene Hilgard did not have the studies of Vasily Dokuchaev to hand, and described how Chernozems might form in forests with humid climates and loamy soils. Autumn leafs and decaying twigs and trunks were incorporated in the surface soil but: "… active animal agencies carry the organic remnants bodily down. In heavy clay soils the humus of the lower soil layers must of necessity be derived from the decay of the roots only. This origin is claimed by Peter Kostichev [sic] for the high content of black humus in the tchernozem or black earth of Russia." [1] Pavel Kostychev had also shown how nitrogen depletion was the cause for crop failures on the Chernozems. George Merrill's book, *A treatise on Rocks, Rock-Weathering and Soils,* also published in 1906, viewed the Chernozems formation of Russia as: "…a local phase of the loess, the color being due to the prevalence of organic matter." [4]

In the 1913 publication *Soils of the United States*, the soils of the Great Plains were described by Macy Lapham, who wrote that many soils were developed in wind-deposited material, giving rise to the 'soils of the Windlaid province' [5]. The Great Plains were dominated by prairie vegetation which was sometimes used interchangeably for steppes and although both referred to grasslands, prairie had tall-grass vegetation whereas steppe was dominated by short grasses. In the *Soils of the United States*, soils were grouped by provinces, soil series and soil types—the last and most specific grouping being according to soil texture. About 65 soil series had been recognized in the Great Plains, more than half of these had silty loam textures; some of the soil series derived from loess had thick topsoils: "…black when moist. The subsoils are light brown, brown, or gray to dark drab, rather heavy and compact, and frequently calcareous". Because of the ignorance of Russian studies, it took 20 years before the *Bureau of Soils* adopted the term Chernozem [6].

At the *First International Congress of Soil Science* in 1927, Curtis Marbut presented a new scheme for soil classification. He recognized: "…that a classification of a group of things does not in itself increase our knowledge of those things. It is fundamentally an arrangement to facilitate the use of knowledge. The discovery of the characteristics of the bodies classified and the determination of their relationships, significance and relative importance constitute the contribution to human knowledge, rather than the arrangement." At the highest level, he placed 'mature soils'—those with a fully developed profile; immature soils were subgroups. He proposed Pedalfers and Pedocals and introduced Chernozems as a subgroup of the Pedocals. The Chernozems were formed by, what he called, climatic and biotic forces, and they became a Great

Soil Group in the American soil classification system [7]. In 1930, the term Chernozem appeared in a textbook on American soils [8].

For Curtis Marbut, the black prairie soils or Chernozems were an inspiration [9], they were pedological royalty [8]. They had been the object of the foundational studies in soil science [10, 11], and they were important for agricultural production. The decaying grass roots resulted in the thick, black, fertile topsoil but the organic matter was stabilized by calcium and magnesium. In Russia, it was perceived early on that the organic matter content of the Chernozems was related to the climate of a specific zone but, according to Konstantin Glinka, it was perhaps not as regular or zonal as Vasily Dokuchaev and Nikolia Sibirtsev had thought [10]. In the 1920s, evidence suggested that Chernozems not only covered extensive areas in Russia, but also occurred in the USA (Dakotas, Nebraska, Texas), Canada, Argentina, and perhaps in South Africa and Eastern Australia [10]. At the *Second International Congress of Soil Science* held in Russia in 1930, the field excursion went through the Chernozem belt and the participants examined a Chernozem at the Agricultural Experiment Station in Kharkov in Ukraine. After the congress, the term Chernozems became more widely used (Fig. 5.1).

Hans Jenny referred to studies on Chernozems throughout the *Factors of Soil Formation* book and explored how Chernozems differed with relief, rainfall, and under different precipitation-evaporation ratios—the so-called NS quotients. He studied the lime content of Chernozems across North America, and showed that the depth to lime increased but its concentration decreased with higher rainfall [12]. The book related several soil properties to the factors of soil formation across large areas. When Hans Jenny took up a position at the University of Missouri in 1927, he was keen to see the Chernozems of the Great Plains, as he reminisced in 1980: "…climatic comparisons of Europe and the United States suggested that the famous Russian Chernozem, a soil rich in humus and having a calcium carbonate horizon in the subsoil, might also have arisen in central Kansas and Nebraska. I was longing to meet this idol of a climatic soil profile, and on a field trip to western Missouri I talked my graduate student companion (Roy Hockensmith) into driving the old model-T Ford westward deep into Kansas, at the 25 miles per hour it was capable of doing. We found the missing link and were elated, having seemingly confirmed the climatic principle of soil genesis. Alas, back in Columbia we were lambasted for having taken a state car across the state line without prior permission." [13]

Fig. 5.1 Chernozem profile examination at the Agricultural Experiment Station in Kharkov in Ukraine during the excursion of the *Second International Congress of Soil Science* in 1930. Boxes with samples from a Chernozem: A1 0–3 cm, A 10–20 cm, A1 30–40 cm, A1 53–61 cm, B1 67–74 cm, and B1 100–110 cm

Chernozems and Constantin

Constantin Nikiforoff was mentored by Konstantin Glinka who organized many excursions across the Russin empire and Constantin Nikiforoff participated in several of them. One of Constantin Nikiforoff's first papers, *Chernozem Belt of Achinsk District, Yenisie Province* followed an expedition to central Russia in 1913; and in 1916 he published *Morphological Description of the Chernozems of the North Part of the Don Region*. Both papers were in Russian. Some 12 years later, in the summer of 1928, he saw his first Chernozem in the USA.

During the soil survey of the Red River Valley in Minnesota which Constantin Nikiforoff had joined in the summer of 1928, the survey team mapped black soils that they named the 'Barnes soil series'; these soils had been first described in 1914 in Barnes County in North Dakota. In the Red River Valley, the soils had developed in glacial drift on upland prairies. The Barnes Series covered about 7% of the survey area but over 20% in some of the counties. The soils were rich in organic matter with A horizons that were almost black and up to 60 cm thick, a well-developed granular soil structure, and loamy textures. Constantin Nikiforoff recognized their importance: "…generally speaking, the Barnes soils rank among the best agricultural soils, as they are naturally rich in plant nutrients. Their relief promotes early and rapid drying and warming of the soil in spring, and the physical structure of the surface soils provides an excellent seedbed." [14]

In Hennepin County, west of Minneapolis, Constantin Nikiforoff observed a belt of dark colored soils that had developed under grassland, known locally as prairie or humid grassland soils [15]. The soils had the characteristic dark color and granular structure of prairie soils, but they could not be classified Chernozems as they had no carbonate horizon. Chernozems must have a zone of lime accumulation, which was generally better developed under low rainfall and going west. In the east, where the climate was more humid, a carbonate horizon was absent [15]. Some years later, Constantin Nikiforoff observed Chernozems in the state of Washington where they were extensive in the eastern part of the state. He attributed the Chernozems of Washington to: "…a mass effect of a certain natural combination of definite climatic conditions, grass vegetation, and topographical configuration of the general landscape." [16] The Chernozem belt in Washington was interrupted by the Cascade Mountain Range that ran north–south from Washington and Oregon to California. The higher altitude with changes in rainfall and temperature and a different parent material gave rise to forests and Podzols and volcanic soils, amongst others (Fig. 5.2).

In 1936, Constantin Nikiforoff published a paper on the formation of Chernozems reviewing research that had been conducted in Russia [17]. He distinguished the three distinct features of Chernozems: high content of organic matter in the A horizon, accumulation of carbonate salts in the B horizons, and a saturation of cations, especially calcium, on the colloidal or clay complex. He stated: "The Chernozem is a classical representative of the grassland type of soil formation, and as such it stands in distinct contrast with the Podzol and desert soils which represent in the same way the woodland and shrubland types of formation, respectively." [17] The three pedogenic processes forming Chernozems were humification, accumulation of soil organic carbon, and calcification. He regarded humification or humus

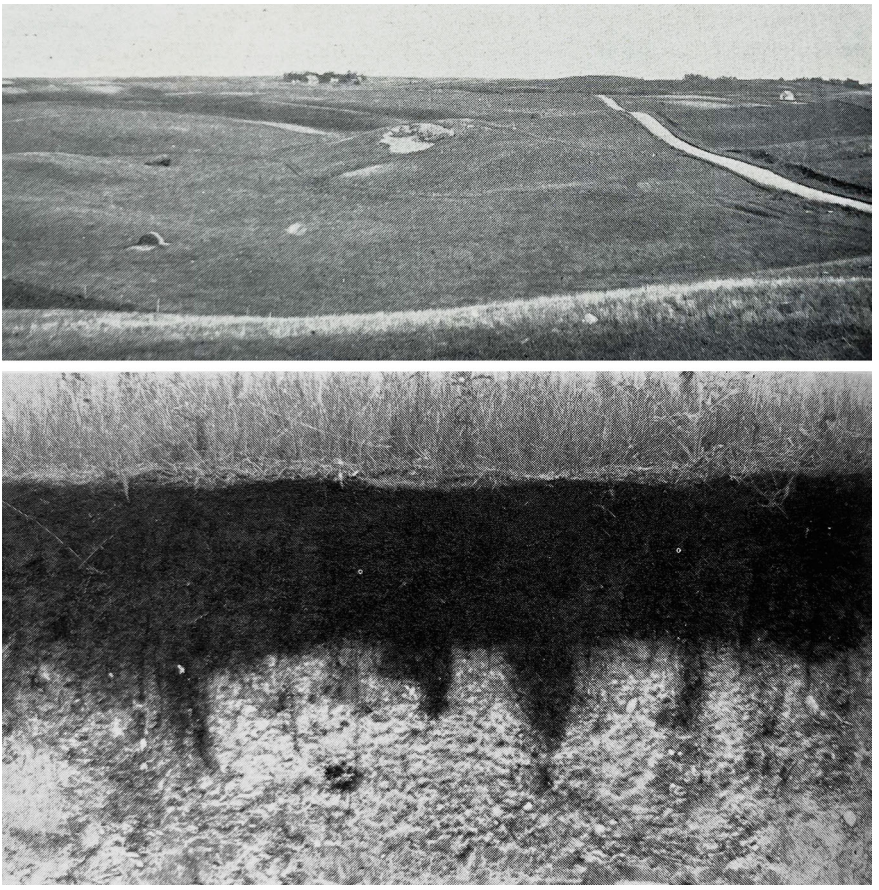

Fig. 5.2 Landscape of the uplands in the Red River Valley of Minnesota dominated by the Barnes soil series. The Barnes loam soil profile was classified as a Chernozem (Calcic Hapludolls). Photos from the 1939 report *Soil survey the Red River Valley area Minnesota (reconnaissance),* lead author: Constantin Nikiforoff

formation as a biochemical process that was fed by the organic residues of the vegetation, including easily decomposable carbohydrates, more resilient carbohydrates such as lignin, and lastly proteins, and fats, waxes and resins. Decomposition of organic residues released carbon dioxide, water and salts that could be taken up by the plants, stored in the soil, or be leached. The process of decomposition and mineralization proceeded slowly, and a range of different substances were formed each with their own decomposition constant. Carbon accumulation in the soil included both accumulation of humus and accumulation of calcium carbonates and to a lesser extent magnesium carbonates. These carbonates were formed when carbon dioxide from the decomposition of organic matter was partly dissolved in the soil solution

and precipitated with calcium released from the weathering from primary minerals. Calcification was the saturation of the clay complex predominantly by calcium, and the result of physicochemical reactions between clay and free bases. He emphasized that carbonate in the subsoil was an essential feature of Chernozems but that the A horizon was often free of carbonates.

Based on the work of Konstantin Glinka, he listed five types of Chernozems: degraded Chernozems, leached Chernozems, deep or fat Chernozems, ordinary Chernozems, and southern Chernozems—they were distinguished based on colors and organic matter levels. For example, the deep or fat Chernozem had more than 10% humus in the top 5 cm, whereas the degraded Chernozem had less than half of that. He calculated the humus stocks for the top 30 cm: there was almost 1,000 tonnes of humus per hectare in the deep or fat Chernozems. If the carbon percentage of the humus was about 60%, it meant about 600 tonnes of soil organic carbon per hectare. Such estimates are close to what has been reported recently for similar soils and depths [18].

Based on limited observations, Curtis Marbut had postulated that the levels of carbonate in the subsoils of Chernozems was higher than in the parent material and regardless of the parent material [7]. He used the presence or absence of the carbonates in the subsoil as a basis for separating the Pedocals and Pedalfers. As mentioned, Chernozems were a subgroup of the Pedocals, and soils that had no carbonates in the subsoil could not be classified as Chernozems. As Constantin Nikiforoff observed in Hennepin County, in humid regions the calcium was leached whereas in drier zones calcium carbonates accumulated with depth. In 'true Chernozems' the calcium originated from calcareous parent material such as calcareous drift and glacial drifts, but not all Chernozems had calcareous parent material. It was possible that the calcium from the weathering of primary minerals was precipitated with the carbon dioxide from decomposition of organic matter. That way non-calcareous parent materials could create Chernozems that: "…have produced and accumulated their own 'pedological' lime." [17] So, Curtis Marbut's observation from the late 1920s that levels of carbonate in Chernozem subsoils was higher than in the parent material proved possible.

Lastly, Constantin Nikiforoff noted that calcium carbonate occurred at shallower depths in the Chernozems of the southern part of Russia compared to the north, which was explained by rising soil solution and less leaching. He concluded that this accumulation of carbonates in the subsoil of the Chernozems (which he termed carbonization) was not fully understood but that climate was the most important factor [17]. His paper also included a general scheme of the pedogenic processes or humus formation showing different pools and fluxes; the scheme is reviewed in Sect. 5.3. Constantin Nikiforoff's

paper on the formation of Chernozems has been cited only about 20 times in the past 85 years [19, 20]. It may be the first example of soil carbon stock calculations and the values are close to recent soil carbon stock assessments of Mollisols.

From Chernozems to Mollisols

Chernozems was introduced by Curtis Marbut in his 1928 classification scheme and for the soils chapter of the *Atlas of American Agriculture* [7, 21]. In 1938, Mark Baldwin, Charles Kellogg and James Thorp drew up a new soil classification scheme because they thought that Curtis Marbut's classification overemphasized climate and vegetation, and because it was difficult to assess whether a soil was mature or immature [22, 23]. They introduced zonal, intrazonal, and azonal soils at the highest level, and Chernozems became a Great Soil Group in the zonal soils [24]. Below the Great Soil Group were the soil series. Their new system did not last long; it was recognized that it was not able to bridge the gap between the Great Soil Groups and the soil series that were used to map the distribution of soils on the ground. The search began for a new system of soil classification.

In the early 1950s, Charles Kellogg delegated Guy Smith to lead a group to devise a classification system that could accommodate all soils, not just the soils of the USA. They wanted to base classification solely on soil morphology, irrespective of imputed genetic processes but Guy Smith found that the concepts of the zonal soils could be maintained if soil moisture and temperature were introduced at a high level, and Charles Kellogg agreed that such an approach would maintain some continuity with previous classifications [25]. A series of approximations was developed and tested to investigate its defects and, thus, gradually approach a workable system [26]. In 1956, a new nomenclature was developed so that each class had a name that was mnemonic and connoted some properties of the soils [27]. The nomenclature was developed by classical linguists [25], and they posited names derived from Greek and Latin, which, unsurprisingly, alienated English-speaking soil scientists. The *7th Approximation* was presented in 1960 at the *International Congress of Soil Science* in Madison, and no longer included Chernozems, Podzols, Solonchaks and Solonetz that had been used for many decades. Chernozem was being used for the last time in the 1957 Yearbook of Agriculture [28], that included a soil map showing the global distribution of Chernozems, including extensive areas in the tropics (Fig. 5.3).

Most soils that were classified Chernozems in the earlier systems became Mollisols in the *7th Approximation* [26], and *Soil Taxonomy* [29, 30]. Mollisols extend most widely in the mid-latitudes of North America, Eurasia,

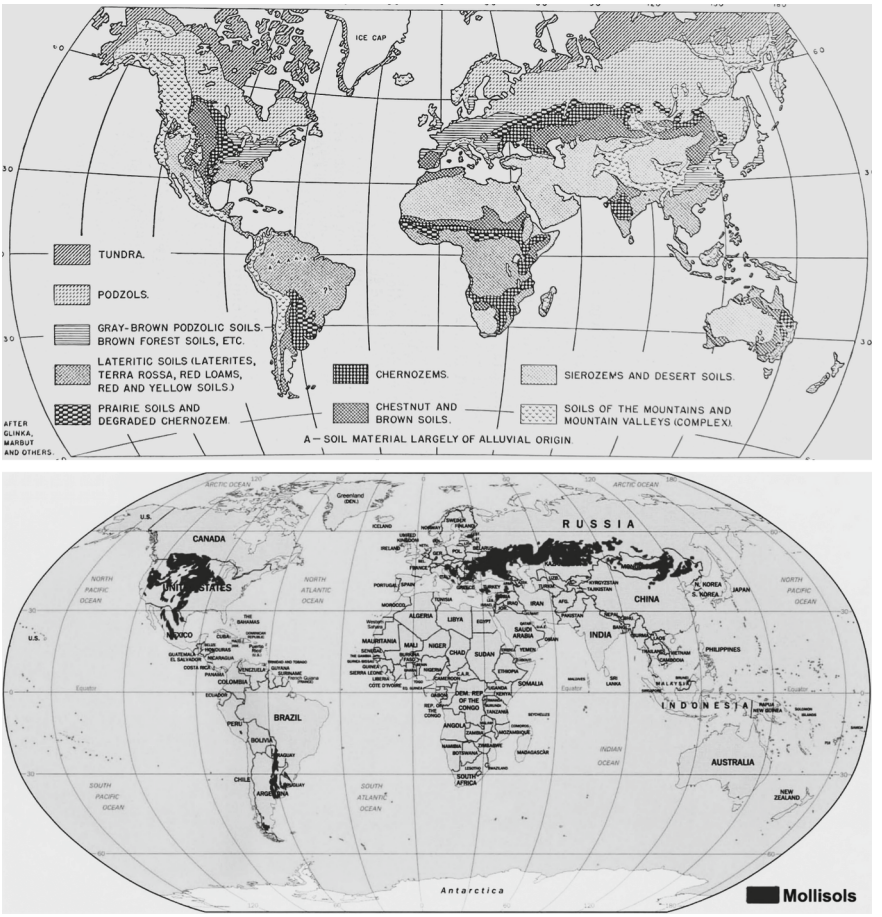

Fig. 5.3 Map of primary soils groups in the world showing Chernozems, prairie soils and degraded Chernozems, based on the studies by Konstantin Glinka, Curtis Marbut, and others. Map from the chapter *Soils and Society* by Charles Kellogg in the 1938 Yearbook *Soils & Men*. Original caption included: "Some interesting similarities and contrasts between the people and social institutions in various parts of the world may be partially explained from this map." No further explanation was given. Lower map shows the distribution of Mollisols (more or less equivalent to Chernozems) from the 2020 paper by Xiangru Xu and others

and South America, notably in Russia, Ukraine, Bulgaria, Romania, Hungary, Germany, Poland, north-east China, USA, Canada, Argentina and Uruguay. They are important for agricultural production and because of the organic matter rich topsoils they play a critical role in the global carbon cycle. It is estimated that Mollisols occupy about 916 million hectares worldwide which is about equivalent to the total land area of the USA. Mollisols account for 7% of the world's ice-free land surface and almost one-third of the land under

cultivation [31]. In the USA, they cover more than 200 million hectares, or 21% of the land area, with extensive areas in the west.

Many Mollisols appear to have formed under different climatic conditions with different vegetation so, if they are degraded, it will be hard to restore the original level of soil organic matter. Several studies have shown that Mollisols may have lost about half of their original soil organic matter content because of soil erosion, long-term cultivation, and climatic changes [32]. Deeper knowledge has been gained about their formation including the mixing by soil organisms, the creation of channels and pores by burrowing animals, and the formation of stable organo-mineral associations and aggregates [33]. The soil organic carbon of Mollisols has received much more research attention than the inorganic carbon [34].

5.2 Soil Organic Matter and Humus

Constantin Nikiforoff contributed the chapter on *Soil Organic Matter and Soil Humus* to the 1938 *Soils & Men* yearbook [35]. Towards the end of 1936, the Secretary of Agriculture, Henry Wallace, asked Charles Kellogg for a comprehensive review about the soils and their uses, to be prepared as the 1938 yearbook. Time was short and Charles Kellogg decided that it had to be a collaborative effort from the best soil scientists across the country. He drew up the structure of the book, invited authors, compiled data, and contributed to several chapters. Roy Simonson, his former student from North Dakota, helped edit the manuscripts. The 1938 yearbook provided a broad overview of soil knowledge, including economic and human aspects [35]. Charles Kellogg oversaw the section that dealt with the fundamentals of soil science, which included a new soil classification scheme [24], and the chapter by Constantin Nikiforoff [36]. *Soils & Men* was published two years after Henry Wallace had made the request; it contained 58 chapters, 1,232 pages and a 44-page summary. It was dedicated to Curtis Marbut, who: "…inspired all associates as well as young men everywhere who were interested in soil science."

Soil Organic Matter

Constantin Nikiforoff's chapter on *Soil Organic Matter and Soil Humus* began with: "One of the most important things in the soil is humus, the product of decayed organic matter. This chapter discusses soil humus from the broadest standpoint, telling what it is, what its functions are; what factors determine whether the supply is large or small and whether it is slowly or

quickly used up; how different types of soil differ in their humus content; how humus is related to the productivity of the soil." [36] He emphasized that an unique aspect of the earth was living matter that resulted from green plants transforming sunlight combined with water, nutrients and carbon dioxide; its distribution over the earth's surface was uneven: "…the regions where natural conditions are favorable for life harbor conspicuous congestions of living matter, whereas regions of the opposite type appear as virtual biological vacuums."

He introduced 'biological pressure' as the relationship between the amount of living matter and the land. Under natural conditions the biological pressure was in equilibrium with the potential capacity to support life. Living matter was made up of many elements but mostly carbon, oxygen, hydrogen, and nitrogen, and water. Portions of the living matter, whether whole organisms or only parts of them, were continually dying and decomposing, but at the same time new matters were being synthesized: "Endless successions of generations have deposited their residues in the soil, from which soil organic matter and soil humus have been formed. In spite of the continual depositing of residues, neither the soil organic matter as a whole nor the humus portion of it accumulates endlessly. They are both unstable and gradually decompose into the simple elemental constituents."

Soil organic matter was defined as the bodies of dead organisms and the residues of living matter deposited on and within the soil. It only comprised the dead residues of organisms and the products of decomposition. He regarded the micro-organisms as part of the soil organic matter, but it also included dead roots, leaves, fruits and stems of plants; carcasses of insects, worms, and animals; living and dead bacteria, fungi, and protozoa; various products of decomposition of the dead residues; and newly synthesized substance of active micro-organisms. Mineralization of soil organic matter yielded water and carbon dioxide, nitrogen and some salt [17]. He noted that all organic residues would eventually be mineralized, and that humus was not stable and only a stage in the decomposition of soil organic matter.

Organic residues did not decompose uniformly, and some substances decomposed quickly, and the result was a mixture of many different compounds formed during the decomposition processes. As he defined humus: "…it has no definite chemical composition, but physically it is a homogeneous, amorphous, dark-colored, and practically odorless material. Fresh organic residues, as well as those in in advanced stage of decomposition which still preserve a specific structure of the organized tissues, are not considered a part of soil humus, although they are sometimes referred to as raw humus." Earlier on he had defined humus as: "…a mixture of many different

substances which decompose at widely different rates. Numerous intermediate products are formed before a complete breakdown occurs. Therefore, the general rate of decomposition of humus is nothing more than a rather rough approximation of the mass effect of numerous reactions which take place in the soil." [37]

Just as he was interested in equilibria in soil formation, Constantin Nikiforoff had ideas about the stability of organic matter in the soil: "…as the organic matter decomposes, new humus is continually being formed, and part of the old is being completely mineralized. The equilibrium between the two processes determines the amount of humus present in a soil at a given time." Young soils generally accumulated humus, and the amount of mineralization increased when a soil matured and was equal to humus addition when the soil was in balance with its environment like in a mature soil. Human activities—which he qualified as: "…that spectacular meddling with nature"—had profound effects on the soil organic matter content through, for example, irrigation of arid lands, drainage of wetlands, deforestation, annual removal of crops, and breaking of sod or tillage. He emphasized that humus acted as a storeroom of mineral plant nutrients but that it was also important because it modified soil structure, color, consistence and the soil moisture holding capacity. Factors that determined the soil organic matter content in soils under grassland, forests, and in desert were reviewed [36], and in some areas cultivation of virgin land had markedly decreased the soil organic matter content, whereas in other areas it had no effect or even increased. He concluded that the maintenance of humus was critical for the use of the soil [36]. The chapter included a diagram of the relationships between the various processes that form and decompose soil humus which he had presented a few years earlier in the Chernozem paper [17].

The *Soils & Men* yearbook was a success. More than 250,000 copies were sold and distributed [28], because the public could see the point of it, and the best soil scientists also wrote good, plain English. Two decades on, another yearbook was published devoted to soil: the 1957 Yearbook of Agriculture, simply entitled: *Soil*. Its 784 pages and 88 chapters were arranged under: Principles, Fertility, Practices, Soil care, Moisture, Systems, Regions and Special Uses. There were chapters by Charles Kellog, Sterling Hendricks, Lyle Alexander, Roy Simonson and dozens of soil and agricultural experts. The foreword was by Ezra Taft Benson who was the Secretary of Agriculture, a Mormon and a farmer, and he announced: "Continuing thorough research in the management of soil and water is a vital part of the long-range program. Not only must we learn more about the management of our soil and water; we must encourage the wider dissemination and application of

the results of this research." [28] Compared to the 1938 yearbook, more attention was given to soil management and agronomic principles; far less attention was paid to foundational soil studies. If the 1938 yearbook carried the imprint of Curtis Marbut's concept of soil science, the 1957 yearbook was more like Charles Kellogg—soil interpretation and soil management, and less fundamental. Charles Kellogg oversaw the 1957 yearbook and asked Constantin Nikiforoff for a contribution, but to his disappointment he refused. Constantin Nikiforoff retired in 1957.

5.3 Carbon Cycle

In his review of Chernozems, Constantin Nikiforoff included diagrams on the pedogenic cycling of humus and soil carbon. The first diagram showed the biogeochemical pathways inputs of plant residues, which he termed the short cycle [17, 36] (Fig. 5.4). The second pathway, the long cycle, encompassed carbon and carbon dioxide pools of the atmosphere, living matter, soil and lithosphere and the fluxes between them [38]. Before presenting those two carbon cycles, first something more about their origin and the development of the carbon cycle concept.

The element carbon was recognized in 1789 by the French nobleman and chemist Antoine Lavoisier (1743–1794) who is also known for his discoveries of hydrogen and the role of oxygen in combustion. Throughout the nineteenth century there was a search for how carbon entered plants, how carbon dioxide was released by respiration, how geological phenomena influenced the composition of the atmosphere, and the various sources and sinks of carbon [39]. Over time, studies on carbon were undertaken by geochemists who quantified pools and fluxes, and microbiologists who focused on decomposition and cycling of organic materials. One of the first short-cycle carbon diagrams was presented in Selman Waksman's *Humus* book of 1936 [40]. The first long-term carbon cycle was developed by Vladimir Vernadsky (1863–1945) who introduced the term 'carbon cycle' in a 1924 book published in French. He estimated the main fluxes of the global carbon cycle such as those between the biosphere, oceans, carbonate and coal formations, and volcanoes, and introduced the idea of geochemical pools and the dynamic equilibrium of element cycles [39], which further developed by Victor Moritz Goldschmidt (1888–1947), became the foundation of the geochemistry discipline [41].

Victor Goldschmidt was born in Switzerland, moved with his family to Norway in 1900, was awarded a PhD at the age of 23 and was appointed professor and director of the Mineralogical Institute when he was 26. The

dearth of raw materials in the First World War drew him to geochemistry. In 1929 he joined the University of Göttingen, and six years later, driven out by anti-Semitism, he returned to Norway. During the German occupation, he was interned in a concentration camp but, in 1942, escaped to Sweden and, then, to the UK where he worked at the Macaulay Institute and at Rothamsted and met Alex (Sandy) Muir. After the war, he returned to Oslo where he died in 1947. He left a large manuscript that was edited by Sandy Muir: *Geochemistry* [42]; well over 700 pages including the long carbon cycle.

The Short Carbon Cycle

Selman Waksman drew a schematic representation of decomposition of plant residues and humus formation the in the soil. He defined humus as a mixture of the original plant material resistant to further decomposition, substances undergoing decomposition, and compounds synthesized

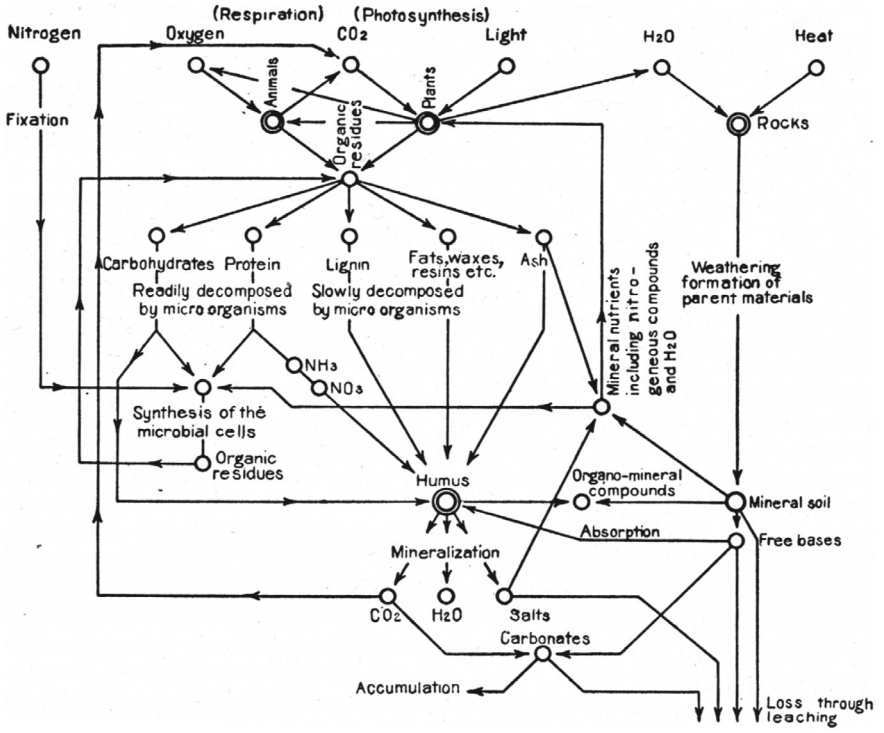

Fig. 5.4 Relationship between the various processes in the formation and decomposition of humus in the soil. Diagram from the chapter *Soil Organic Matter and Soil Humus,* by Constantin Nikiforoff in the 1938 Yearbook *Soils & Men*

by micro-organisms. He recognized three main pools (plant material, soil, microbes) and numerous processes and fluxes. Plant material consisted of cellulose, proteins, lignin and undecomposed residues—the latter which form humus, whereas the first three would be decomposed by microorganisms and eventually also add to the humus pool. For decomposition and humus formation soluble nitrogen compounds and bases were important soil constituents.

Selman Waksman had recognized three main pools and several fluxes, and Constantin Nikiforoff added animal, rock, and organic residue pools. He also related organic residues to humus formation, and processes such as photosynthesis, mineral weathering and nitrogen fixation to pathways between elements, compounds and microbial cells. He distinguished two phases: the synthesis and formation of organic matter by living organisms, followed by the decomposition and mineralization of that material in the soil. Powered by solar radiation and chlorophyll, plants use water, nutrients and carbon dioxide and produced organic material. When the plants died or were eaten by animals, the organic material eventually returned to the soil where it was decomposed and mineralized. As he had noted before, some materials, such as proteins, were easily decomposed by micro-organisms whereas others decomposed more slowly. The short-cycle diagram also included the interaction between humus and mineral soil that he termed organo-mineral compounds. Nitrogen entered the system through biological fixation whereas other nutrients were derived from the weathering of primary minerals, but in mature soils these elements were recycled.

Humus was composed of different organic materials and the product of decayed organic matter [36]. It had no definite chemical composition, and he considered it a homogeneous, amorphous, practically odorless, dark-colored material. Fresh organic residues were not part of humus, and he referred to this as ‘raw humus’. Soil organic matter included residues of the living matter and the bulk of bodies of micro-organisms. Importantly: humus was not stable; over time it would be completely mineralized, but the content at any given soil and location depended on the balance between mineralization and newly formed humus.

Since these early short-cycle biochemical diagrams, theories have been developed, and models have attempted to quantify pools and fluxes. For several decades it was widely held that soil organic matter decomposition yielded humic substances and humus was formed that was resistant to decomposition [43–45]. Soil organic matter was considered to be consisting of inherently stable and chemically unique compounds, often called ‘recalcitrant humus’. More recently, it has been claimed that soil organic matter

is in a continuum of progressively decomposing organic compounds, and for that reason the term humus should be abandoned [46]. This is essentially how Constantin Nikiforoff and others in his era viewed humus: not stable or recalcitrant but, over time, completely decomposed and mineralized [37]. The concept of organo-mineral interactions was investigated by Selman Waksman in the 1930s [40], and has since received much research attention [47, 48]. The alchemy of humic substances, disputed by some, celebrated by others, remains a line of research.

The Long Carbon Cycle

The long carbon geochemical pathways, as presented by Constantin Nikiforoff, included estimates of the carbon pools in the atmosphere, living matter, soil, fossil fuel and rocks [38] (Fig. 5.5). Carbon dioxide in the atmosphere was taken up by photosynthesis on land and in the oceans, at a rate of about 3 to 10% of their totals. About half the carbon in the living matter ended up in the land. In the long term, some of the carbon ended up in lithosphere (coal, carbonate rock) and Constantin Nikiforoff termed that 'juvenile carbon' that through weathering and oxidation, eventually returned to the atmosphere. These carbon pools and fluxes were first estimated by Vladimir Vernadsky whom, in the late 1920s, postulated that the different carbon pools had remained more or less constant since pre-Cambrian times, that is over 540 million years ago [38].

Soil carbon did not come from the parent material—the average content of carbon in igneous rocks was less than 0.1%. The content of organic carbon in some soils under grassland well over 5%, and most, if not all, of that had come from the vegetation. Constantin Nikiforoff pointed out, however, that photosynthesis was not the only means of entry of carbon into the soil, as dissolved carbon dioxide also entered the soil in rainwater. He estimated that carbon lost by respiration was about 15% of the carbon fixed by photosynthesis. Not all carbon dioxide produced by oxidation of organic carbon returned immediately to the atmosphere; some carbon dioxide was dissolved in the soil solution and reacted with free bases to form carbonates. As noted, some organic carbon also escaped oxidation and ended up in the long geochemical cycle deposits (peat, coal, oil and natural gas). An unknown quantity of carbon was released by the solution of limestones and other calcareous rocks.

Constantin Nikiforoff estimated that photosynthesis fixed about 18 billion metric tons of carbon per year. Recent estimates have shown that photosynthesis of terrestrial plants absorb about 123 Gt or Pg C from the atmosphere every year [49]. A petagram (Pg) is 10 to the 15 g, equivalent to a gigatonne

or a billion metric tonnes. Converting carbon dioxide to carbon, Constantin Nikiforoff estimated the atmospheric carbon pool at 599 Pg, and 16,384 Pg of carbon in the oceans. The biotic pool or living matter was estimated to be about 708 Pg, and the total carbon in the soil was 508 Pg of carbon. He calculated that the combined soil and biotic pool, called the terrestrial carbon pool, was about 2.5 times larger than the atmospheric pool.

Since that time, especially in the last 20 years, the five main carbon pools (atmosphere, oceans, biotic, soil and fossil) have been assessed by a range of new and refined measurements techniques and some consensus has been reached on the pool sizes [50, 51]. The atmospheric pool amounts to 780–875 Pg and is about 1.5 times larger than Constantin Nikiforoff's estimate. He also underestimated the terrestrial carbon pool, especially the soil pool which recent estimates have shown to be about 3,600 Pg of carbon. The terrestrial carbon pool is estimated to be about 4 to 5 times larger than the atmospheric carbon pool. Constantin Nikiforoff did not have the benefit of remote sensing, soil data were few, and earth system models had not been developed but he correctly identified the different pools and possible fluxes between them and although his absolute values were wrong, the ratios between these pools were not far off.

Research on global carbon pools and fluxes has vastly expanded and includes, for example, the residence time of organic matter in different pools, modelling of decomposition, radiocarbon dating, remote sensing and real time measurements, the role of fungi in soil carbon sequestration, and a bouquet of earth system models [52]. Progress has been made in rapid assessment of soil organic carbon, and improved methods for mapping the soil carbon content across large areas that did not exist at the time of Constantin Nikiforoff's studies. Nowadays, many study agricultural landscapes and how carbon in cultivated soils is affected by tillage or other management factors which was not considered by Constantin Nikiforoff who reviewed the formation and decomposition of humus only in the soils of the forests, grasslands and deserts. Some current research is driven by a need to understand the role of soil carbon in maintaining soil fertility, how carbon dioxide and other greenhouse gases affect the climate, and how soil carbon can be maintained, increased and stored for long period as to offset the rise in atmospheric carbon dioxide. When Constantin Nikiforoff presented his carbon cycling diagrams the global atmospheric carbon dioxide concentration was about 300 ppm, now it exceeds 425 ppm. The consequence of that on the earth system is widely researched but he would probably argue that its effects on pedogenic cycles are not studied adequately.

5.4 Climate Change

Soil scientists, pedologists in particular, have always had an interest in the climate and how it affects the formation and distribution of soil. Until the mid-1800s, soils were generally seen as weathering products of the underlying rock. A new appreciation of the role of climate and vegetation in soil formation and the pattern of soil cover came first in Russia and, more grudgingly, in America. In the first part of the twentieth century, soils were grouped as zonal, intrazonal or azonal outcomes. With growing knowledge of soil patterns and the unravelling of the interacting state factors of soil formation, it was recognized that, at the global level, climate may explain soil distribution but that, in detail, there were inconsistencies. Constantin Nikiforoff considered climatic effects in most of his studies, from the Siberian cold and the blister formation to the cracking soils of the Red River valley, and deserts in California. He realized the importance of climate for soil formation and evolution and that changes in the climate changed the equilibrium between the soil and its environment. Naturally, he was interested in the effect of a changing climate on the soil.

In 1943, the geologists Kirk Bryan and Claude Albritton (1913–1988) published a paper entitled *Soil Phenomena as Evidence of Climate Change*s [53]. It presented results of studies on polygenetic soils that suggested an approach for investigating climatic changes during the Quaternary period: "If a soil is matured in a single period having a relatively uniform climate, there results the normal soil familiar from textbook description. It is a monogenetic soil. If, however, two time intervals of differing climate are involved so that one type of profile is superimposed on another, or if more than two time intervals are involved, the soil is polygenetic." As Constantin Nikiforoff had presented earlier [37], Kirk Bryan and Claude Albritton distinguished between 'soil development' that took place under a constant climate, and 'soil evolution' responding to a changing climatic. They focused on 'soil development' and noted that evidence for climatic changes was found in the deeper soil, such as, for example, a change from a cold humid to a warm humid climate resulting in a change in colour of iron hydroxides (Fig. 5.5).

An early publication on climate change published in 1951 [54], listed evidence that was collected by glaciologists, geographers, meteorologists, archaeologists, physicists and biologists. Change in the world climate from the mid-1850s to the 1950s included a rise in temperature following the industrial revolution and the exploitation of the Earth's resources. The consequences would be the melting of the glaciers and polar pack ice, and many of the world's drylands would be affected. It concluded: "Should the picture that

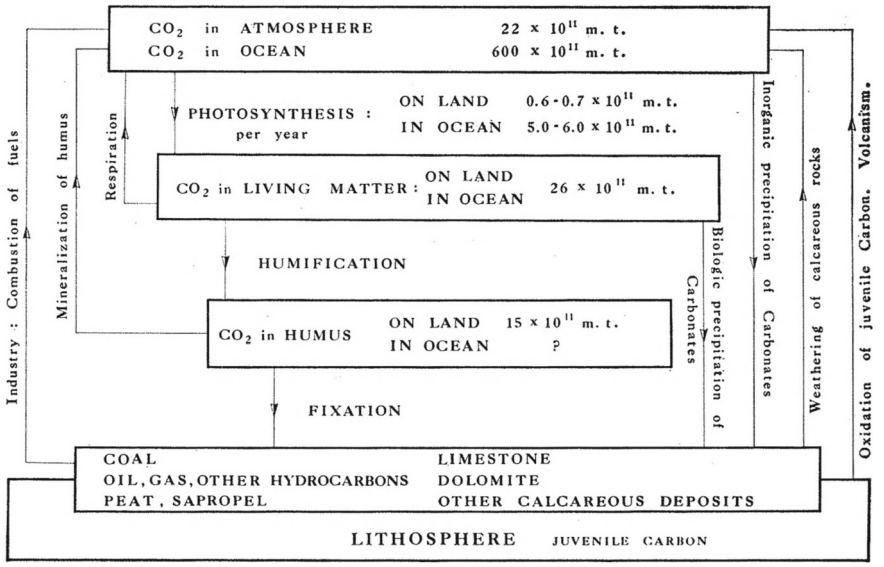
CO_2 in ATMOSPHERE 22 × 10^{11} m. t.
CO_2 in OCEAN 600 × 10^{11} m. t.
PHOTOSYNTHESIS : per year
ON LAND 0.6-0.7 × 10^{11} m. t.
IN OCEAN 5.0-6.0 × 10^{11} m. t.
CO_2 in LIVING MATTER : ON LAND IN OCEAN 26 × 10^{11} m. t.
HUMIFICATION
CO_2 in HUMUS ON LAND 15 × 10^{11} m. t. IN OCEAN ?
FIXATION
COAL
OIL, GAS, OTHER HYDROCARBONS
PEAT, SAPROPEL
LIMESTONE
DOLOMITE
OTHER CALCAREOUS DEPOSITS
LITHOSPHERE JUVENILE CARBON
Industry : Combustion of fuels
Mineralization of humus
Respiration
Inorganic precipitation of Carbonates
Biologic precipitation of Carbonates
Weathering of calcareous rocks
Oxidation of juvenile Carbon. Volcanism.

Fig. 5.5 Long-term geochemical cycles of carbon, estimates based on the studies by Vladimir Vernadsky and others. The pools (e.g. atmosphere, humus) are in metric tonnes, and according to the original figure caption: "Their purpose is merely to give some idea about the probable order of magnitude." Diagram from the 1959 paper by Constantin Nikiforoff on the *Reappraisal of the Soil*

has here been painted appear too dismal, it may be brightened by the thought that, should modern man succeed in mitigating the secondary effects of the changing climate, the primary movement may be sufficiently slow to afford to succeeding generations ample time to adjust themselves to the change, and that while, on the one hand, deserts may be expanding, on the other, the recession of arctic conditions is opening up new tracts of land for human habitation, and finally, a little cautious optimism may possibly be permitted in respect of the researches in the field of rain-making." [54]

In 1953, Constantin Nikiforoff contributed a chapter to the book *Climate Change. Evidence, Causes, and Effects* following a two-day conference organized by the American Academy of Arts and Sciences [55]. The conference contributions covered a range of topics including climate and life, civilization, race, ice ages, astronomical theory, solar variation, radioisotope dating, tree-ring evidence, paleolimnology and whether there was climate change or just climate cycles. There appeared to be no agreement and, according to the editor: "…it suggests that we shall not all be simultaneously wrong. It means that searching and critical analyzing must go on." Constantin Nikiforoff's chapter, entitled *Pedogenic Criteria of Climate Changes,* described some

key characteristics of soils (soil is not static; soil is a function of the environment rather than a product of the environment) and he listed how the pedogenic characteristics were inherited (material not obliterated by pedogenesis), acquired (not present in the initial material but acquired in the soil by natural processes), or introduced (artificially imparted to the soil especially by agricultural practices). His focus was on soil evolution under a changing climate noting that soils were capable of changes but that it would not lead to the development of new and higher soil species. Soil evolution was an endless readjustment to changes in climate, relief, parent material and vegetation. Some soils were polygenetic, which meant that a soil had characteristics that could not have been acquired under existing conditions, such as examples of relict laterization in Pennsylvania, New Jersey and Maryland, traces of subarctic climate in soils of the tundra with solifluction and cryoturbation, and the accumulation of carbonates of soils in the steppes [55].

Constantin Nikiforoff could not have foreseen how soils and, in particular, soil carbon would become a focus of studies on global change. In the early 1950s, the Swedish meteorologist Bert Bolin (1925–2007), studying the natural carbon cycle, recognized changes in ecosystems related to the increasing concentration of carbon dioxide in the atmosphere. In 1959, he cautioned the US National Academy of Sciences that a 25% increase in carbon dioxide would cause global heating. In 1970, he summarized human influence on the carbon cycle: "The greatest disturbances of which we are aware are those now being introduced by man himself. Since his tampering with the biological and geochemical balances may ultimately prove injurious—even fatal—to himself, he must understand them much better than he does today. The story of the circulation of carbon in nature teaches us that we cannot control the global balances. Therefore we had better leave them close to the natural state that existed until the beginning of the Industrial Revolution. Out of a simple realization of this necessity may come a new industrial revolution." [56] In 1988, Bert Bolin became the first chair of the Intergovernmental Panel on Climate Change (IPCC).

Hans Jenny published a paper in 1980 entitled *Alcohol or Humus* [57], that was prompted by the energy crisis and the proposed plant biomass conversion to fuel. He emphasized that humanity has the power to modify state factors by altering the heat balance, aerosol enhancement of the ozone layer, and carbon dioxide enrichment through fossil fuel burning and cutting forests. He predicted that the global atmosphere would contain 600 ppm carbon dioxide by the year 2030 (current estimates are that it will be 440 ppm by 2030). Since Hans Jenny's paper from 1980, there has been an increasing interest in the relation between soils and climate change. Soils were judged

to play a key role as sink and source of greenhouse gasses [58, 59], but the issue needed more detailed investigation. This was reworded in 1990: "…a clear need for a concentrated effort for the collection of geo-referenced and machine-readable information on quantified soil and land attributes, as a prerequisite for an accurate assessment of the present day contribution on soils and their cover to the greenhouse system, as well as for an estimation of the influence of any future changes in soil and land cover conditions on a surmised global warming." [60] Early clues for recognizing and interpreting past climates came from the combination of pedologic and geologic data begun by Kirk Bryan [53]. Many recent studies have focused on the loss of soil organic carbon and emission of greenhouse gases but very few study the effect of the changing climate on soil. One may surmise that the pedogenic criteria of climate changes offer a great opportunity for research.

References

1. Hilgard EW. Soils, their formation, properties, composition, and relation to climate, and plant growth. New York: The Macmillan Company; 1906.
2. Moon D. The international dissemination of Russian genetic soil science (pochvovedenie), 1870s–1914. J Reg Hist. 2018;2:75–91.
3. Joffe JS. Pedology (with a foreword by C.F. Marbut). New Brunswick: Rutgers University Press; 1936.
4. Merrill GP. A treatise on rocks, rock-weathering and soils. New York: The MacMillan Company; 1906.
5. Marbut CF, Bennet HH, Lapham JE, Lapham MH. Soils of the United States. Washington: Government Press Office; 1913.
6. Hartemink AE. Soil Science Americana. Cham, Switzerland: Springer; 2021.
7. Marbut CF. A scheme for soil classification. Paper presented at: first international congress of soil science, Washington DC; 1928.
8. Wolfanger LA. The major soil divisions of the United States. A pedologic-geographic survey. New York: John Wiley & Sons; 1930.
9. Marbut CF. The excursion. In: Waksman S, Deemer R, editors. Proceedings and paper first international congress of soil science. transcontinental excursion and impressions of the congress and of America. Washington D.C.: The American Organizing Committee of the First International Congress of Soil Science; 1928. p. 40–88.
10. Glinka KD. The great soil groups of the world and their development (translated from German by C.F. Marbut). Ann Arbor, Michigan: Mimeographed and Printed by Edward Brothers; 1928.

11. Dokuchaev VV. Russian Chernozem. Selected works of V.V. Dokuchaev. Volume I (translated in 1967). Washington DC: Israel Program for Scientific Translations. U.S. Department of Agriculture; 1883.
12. Jenny H. Factors of soil formation. A system of quantitative pedology. New York: McGraw-Hill; 1941.
13. Jenny H. The soil resource. Origin and behavior. New York: Springer-Verlag; 1980.
14. Nikiforoff CC, Hasty AH, Swenson GA, et al. Soil survey the Red River Valley area Minnesota (reconnaissance). Washington: United States Department of Agriculture. Bureau of Chemistry and Soils; 1939.
15. McMiller PR, Nikiforoff CC, Fieger EA, et al. Soil survey of Hennepin County, Minnesota. Washington DC: Bureau of Chemistry and Soils. USDA; 1929.
16. Nikiforoff CC. The inversion of the great soil zones in Western Washington. Geogr Rev. 1937;27(2):200–13.
17. Nikiforoff CC. Some general aspects of the Chernozem formation. Proc Soil Sci Soc Am. 1936;1:333–42.
18. Wang S, Wang Z, Heinonsalo J, Zhang Y, Liu G. Soil organic carbon stocks and dynamics in a mollisol region: a 1980s–2010s study. Sci Total Environ. 2022;807: 150910.
19. Jenny H, Gessel SP, Bingham FT. Comparative study of decomposition rates of organic matter in temperate and tropical regions. Soil Sci. 1949;68:419–32.
20. Molina JAE, Smith P. Modeling carbon and nitrogen processes in soils. Adv Agron. 1998;62:253–98.
21. Marbut CF. Soils of the United States. Part III. In: Baker OE, editor. Atlas of American agriculture. Washington: United Sates Department of Agriculture. Bureau of Chemistry and Soils; 1935. p. 1–98.
22. Paton TR, Humphreys GS. A critical evaluation of the zonalistic foundations of soil science in the United States. Part I: The beginning of soil classification. Geoderma. 2007;139(3–4):257–67.
23. Brevik EC, Hartemink AE. Soil maps of the United States of America. Soil Sci Soc Am J. 2013;77(4):1117–32.
24. Baldwin M, Kellogg CE, Thorp J. Soil classification. Soils & Men. Washington DC: United States Department of Agriculture; 1938. p. 979–1195.
25. Forbes TR, editor. The Guy Smith interviews: rationale for concepts in soil taxonomy. SMSS Technical Monograph no. 11. Washington DC: USDA Soil Conservation Service; 1986.
26. Soil Survey Staff. Soil classification. A comprehensive system, 7th approximation. Washington D.C.: Soil Conservation Service. United States Department of Agriculture; 1960.
27. Heller JL. The nomenclature of soils, or What's in a name? Soil Sci Soc Am J. 1963;27(2):216–20.
28. United States Department of Agriculture. Soil. The yearbook of agriculture. House Document No. 30. Washington: United States Department of Agriculture. United States Government Printing Office; 1957.

29. Soil Survey Staff. Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys. Agricultural Handbook no. 436. Washington DC; 1975.
30. Soil Survey Staff. Soil taxonomy. 2nd ed. Washington DC: USDA National Resources Conservation Services; 1999.
31. Labaz B, Hartemink AE, Zhang Y, Stevenson A, Kabała C. Organic carbon in Mollisols of the world—a review. Geoderma. 2024;447.
32. Xu X, Pei J, Xu Y, Wang J. Soil organic carbon depletion in global Mollisols regions and restoration by management practices: a review. J Soil Sediment. 2020;20(3):1173–81.
33. Kogel-Knabner I, von Lutzow M, Guggenberger G, et al. Mechanisms and regulation of organic matter stabilisation in soils. Geoderma. 2005;128(1–2):1–2.
34. Gozukara G, Hartemink AE, Zhang Y. Factors driving inorganic carbon levels in the soils of the conterminous USA. Catena. 2025;252.
35. United States Department of Agriculture. Soils and men. The year book of agriculture. House Document No. 398. Washington United States Department of Agriculture. United States Government Printing Office; 1938.
36. Nikiforoff CC. Soil organic matter and soil humus. Soils & men. Washington DC: United States Department of Agriculture; 1938. p. 929–37.
37. Nikiforoff CC. Fundamental formula of soil formation. Am J Sci. 1942;240:847–66.
38. Nikiforoff CC. Reapprasail of the soil. Science. 1959;129:186–96.
39. Galvez ME, Gaillardet J. Historical constraints on the origins of the carbon cycle concept. Cr Geosci. 2012;344(11):549–67.
40. Waksman SA. Humus. Origin, chemical composition, and importance in nature. Baltimore: The Williams & Wilkins Company; 1936.
41. Müller A. Viktor Moritz Goldschmidt (1888–1947) and Vladimir Ivanovich Vernadsky (1863–1945): the father and grandfather of geochemistry? J Geochem Explor. 2014;147:37–45.
42. Goldschmidt VM. Geochemistry (edited by Alex. Muir). Oxford: Clarendon Press; 1954.
43. Mahieu N, Olk DC, Randall EW. Accumulation of heterocyclic nitrogen in humified organic matter: a N-15-NMR study of lowland rice soils. Eur J Soil Sci. 2000;51(3):379–89.
44. Rovira P, Vallejo VR. Labile and recalcitrant pools of carbon and nitrogen in organic matter decomposing at different depths in soil: an acid hydrolysis approach. Geoderma. 2002;107(1–2):109–41.
45. Lorenz K, Lal R, Preston CM, Nierop KGJ. Strengthening the soil organic carbon pool by increasing contributions from recalcitrant aliphatic bio(macro)molecules. Geoderma. 2007;142(1–2):1–10.
46. Lehmann J, Kleber M. The contentious nature of soil organic matter. Nature. 2015;528(7580):60–8.
47. Hassink J. Effects of soil texture and structure on carbon and nitrogen mineralization in grassland soils. Biol Fertil Soils. 1992;14:126–34.

48. Lavallee JM, Soong JL, Cotrufo MF. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob Change Biol. 2020;26(1):261–73.
49. Dusenge ME, Duarte AG, Way DA. Plant carbon metabolism and climate change: elevated CO_2 and temperature impacts on photosynthesis, photorespiration and respiration. New Phytol. 2019;221(1):32–49.
50. Lal R. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience. 2010;60(9):708–21.
51. Rackley S. Chapter 4—the global carbon cycle. In: Rackley S, Andrews G, Clery D, et al., editors. Negative emissions technologies for climate change mitigation. Elsevier; 2023. p. 67–74.
52. Hartemink AE, Gerzabek MH, Lal R, McSweeney K. Soil carbon research priorities. Progr Soil Sci. 2014:483–90.
53. Bryan K, Albritton CC. Soil phenomena as evidence of climate changes. Am J Sci. 1943;241:469–90.
54. Tidmarsh CEM. The depletion of soil and water resources in relation to climatic change. Soils Fertil. 1951;14:427–30.
55. Nikiforoff CC. Pedogenic criteria of climate changes. In: Shapley H, editor. Climate change. Evidence, causes, and effects. Cambridge: Harvard University Press; 1953. p. 189–200.
56. Bolin B. The carbon cycle. Sci Am. 1970;223(3):124–35.
57. Jenny H. Alcohol or humus. Science. 1980;209(4455):444–444.
58. Scharpenseel HW, Schomaker M, Ayoub A, editors. Soils on warmer earth. Developments in soil science 20. Amsterdam: Elsevier; 1990.
59. Bouwman AF, editor. Soils and the greenhouse effect. Chichester: John Wiley; 1990.
60. Sombroek WG. Geographic quantification of soils and changes in their properties. In: Bouwman AF, editor. Soils and the greenhouse effect. Chichester: John Wiley & Sons; 1990. p. 225–44.